The effects of vibration and aeration on the mechanical and flow behaviour of cohesive powders

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S U M M A R Y

Practice shows that controlled discharge of cohesive, non-free-flowing powdered material from a silo involves great difficulties as a result of arch formation and rat-holing.
Since discharge by gravity is often inadequate a great variety of devices are used in industry in the promotion and control of flow.

A major category of auxiliary equipment is related to vibratory systems. However, in many cases it is impossible to realize discharge at a constant rate. Moreover, the span of flow control is generally limited.
Furthermore, there is a risk of vibratory compaction, resulting in poor flowability.

Another type of flow promoting devices is the so-called pneumatic discharge, in which the material is aerated around the outlet opening of the silo. With this method the solids flow rate can be controlled by means of varying the air supply. In the case of a very cohesive powder the method cannot be used satisfactorily because channeling occurs.

Being part of the present research project, a device has been developed for the controlled discharge of cohesive powdered materials from a silo. The method is based on the application of combined aeration and vibration, accomplished by vibrating a porous bottom plate, by which air is introduced simultaneously around the orifice periphery. As a result the cohesive powder assumes more or less fluid-like properties, thus enabling a pneumatic discharge like a free-flowing powder.

Experiments were performed with both a laboratory scale silo and an industrial scaled bin, confirming the general applicability of the discharge system developed.
The mass flow rate of various cohesive powders was measured as a function of both the air flow rate and interstitial air pressure above the bottom plate. The silo geometry, the orifice diameter, the bed height and the vibration parameters were varied.

Results of this investigation are presented in chapter 1 of this thesis. It has been shown that the relation between the solids flow rate, the air flow rate and the interstitial air pressure is affected by both internal friction and porosity changes of the solids. In its turn the latter phenomena are connected with the cohesion of the material as well as the vibrations applied.

An important step in developing the above-mentioned method using simultaneous aeration and vibration has been the experience that a regular and controllable discharge of cohesive powder can nevertheless be realized by controlling the interstitial air pressure in the direct vicinity of the orifice. Based on this pressure the flow can be described by the mechanical energy balance, i.e. the same relation holds as that describing the flow of a liquid through an orifice. Most of the experimental discharge coefficients amounted to about 0.65 and appeared to be independent of the parameters mentioned above.

Combined aeration and vibration favours "mass flow" in a silo. This proved to be valid as well when free-flowing powders were used.

In order to explain the effects of both vibration and aeration on the flow properties of cohesive powdered materials, investigations were performed into the mechanical behaviour and the mobility of a vertically vibrated powder bed, being the second part of the present research project. A profound analysis of the bed behaviour and further evaluation of theoretical considerations and models developed in literature, are presented in chapter 2 of this thesis.

In numerous publications it has been tried to give a direct relation between the vibration characteristics and their effect on the physical operation like mixing, flow and conveying, heat transfer, vibratory compaction and fluidization. This has resulted in highly simplified models. Since their predictable value appeared to be rather low, the literature review is limited to those models which have been compared directly with the results of experiments on the mechanical bed behaviour. From these investigations further conclusions can be drawn related to the effects of vibration on various applications.

It has been shown that considerations presented in literature are essentially the same. They have in common the basic idea that the bed behaves like a rigid porous solid body, omitting bed deformation.

Resulting from inertia forces an air gap is formed periodically between the powder bed and its vibrating base. Originating from the gap, a pressure gradient will develop, meanwhile air is flowing to or from it. Hence pressure variations occur, propagating in upward direction into the bed.

The work described in this thesis has established that also the latter models have a very limited validity. In contrast with the methods used so far, this has been shown by performing highly dynamic interstitial air pressure measurements at various heights in the powder bed. The experimental pressure curves appeared to differ considerably from model predictions.

It has been shown that the interstitial air pressure is closely related to the bed deformation. The measuring method used, presented a powerful means in the analysis of the mechanical bed behaviour, resulting in the conclusion that inhomogeneous porosity variations occur. Indeed, this could be made visible in the light of a stroboscope and, moreover, recorded with a high speed film camera.

Therefore, a model has been proposed in which the bed is considered to be split up in horizontal, air permeable slices. This so-called "porous slice model" is described at the end of chapter 2. Its flow chart is presented in appendix 1.

The equipment and measuring methods used in the second part of this investigation, are described in chapter 3. Some specific items, viz. a hydraulic vibration system with displacement control, the technique for measuring interstitial air pressure variations with a miniature pressure transducer, and accessory data-acquisition, are described in appendices 2, 3 and 4.

The results of the second part of this investigation are presented in the four sections of chapter 4. Each section is followed by a final discussion and conclusions.

Section A deals with the effects of homogeneous ("elastic") deformation, which are not considered in the porous slice model. The experiments were performed under conditions when these effects are dominant, i.e. at very low vibration intensities.

Dynamic measurements of friction between a vibrated powder bed and a fixed wall are discussed in section D.

Results presented in sections B and C, which are of special practical interest, are summarized below.
According to section B the mechanical behaviour of a vertically vibrated powder bed is affected by various parameters, viz. the waveshape, amplitude and frequency of vibrations, bed height, air flow, wall friction and powder properties. Generally, the bed behaviour at usual vibration intensities, proves to be described satisfactorily by the porous slice model.
Experimental results of the effect of vibration on mobility of a vibrated powder bed are presented in section C. Two criteria for mobility are distinguished, namely the flow - no flow criterion and the flow rate criterion. Initiation of flow proves to be determined by inertia forces caused by the vibrations, as a result of impact of bed layers, whereas the flowability proves to be determined by the size of the vibration induced periodical (positive) air pressure pulses.
The complex mutual dependency of the various factors affecting the bed behaviour discussed in section B, was found to be reflected in the mobility.

A main conclusion drawn from the second part of this study learns that it involves great difficulties to achieve a controlled discharge of a cohesive powder from a silo, by applying vibration alone.
This has to be attributed to the low predictability and complex dependency of the vibration induced air pressure pulses.
The solution to this problem is shown in the first part of this thesis. The control of the (mean) interstitial air pressure in the direct vicinity of the orifice, by means of varying a separate gas supply, enables an accurate adjustment of the solids flow rate.

Finally, some properties of the powders used are mentioned in chapter 5.
For further characterization of these powders a triaxial cell has been developed. It proved to be suitable for investigations into the failure behaviour of powders, under a well defined state of stress.
Being part of another research project carried out at the University of Groningen, this apparatus has been used for a fundamental study on the mechanical properties of cohesive powders.